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Multidimensional Models Used in Rivers and Streams

by N. K. Raphelt and M. P. Alexander

PURPOSE: The purpose of this Coastal and Hydraulics Engineering Technical Note is to introduce state-of-the-art applications of multidimensional models with sediment transport capabilities to solve sedimentation problems in rivers and streams.

INTRODUCTION: The term multidimensional encompasses both two- and three-dimensional models. Models of this type typically include both hydrodynamics and some degree of sediment transport capabilities. Two modeling applications are presented using models with advanced sediment transport capabilities: (a) the lower Apalachicola River using the three-dimensional model CH3D-SED, and (b) the Red River Waterway at the John H. Overton Lock and Dam (JHO) downstream approach channel using the model RMA2-SED2D.

THE APALACHICOLA RIVER APPLICATION: Dredged material disposal that is sometimes used on inland waterways involves the placement of the dredged material along the banks of the waterway. During high-water periods, these sediments are then either swept back into the stream or mechanically pushed into the waterway. This type of dredged material disposal is often referred to as mechanical redistribution. The assumption in this operation is that the currents generated by the high-water flows will sweep the previously dredged sediment downstream of the dredged channel. Numerical prediction tools can be used to assess if the sediments moving from the riverbank back into the waterway are indeed transported away from the dredging site or redeposited within the dredging site.

To provide such a prediction tool, a three-dimensional model called CH3D-SED was used for simulating the movement of dredged material disposal on riverbanks and the subsequent fate of that material. A three-dimensional modeling approach was required due to the complex secondary current patterns that typically exist in river bendways.

Background: The Apalachicola River (Figure 1) is formed by the confluence of the Chattahoochee and Flint Rivers. The drainage basin encompases 19,200 square miles in Georgia, Alabama, and Florida. The Apalachicola River is part of a navigation system known as the Apalachicola-Chattahoochee-Flint Waterway. It was authorized by the River and Harbors Act of 1945 and called for the construction of a 2.74-m (9-ft) deep by 30.48-m (100-ft) wide navigation channel. The navigation channel was initially dredged in 1958 to provide adequate depths. Since then annual dredging has been needed to maintain the project. The majority of the dredging occurs within three problem reaches of the river, namely, Bluntstown (Navigation Mile (NM) 76-81), Chipola Cutoff (NM 39-42), and Corley Slough (NM 35-37) as shown in Figure 1.

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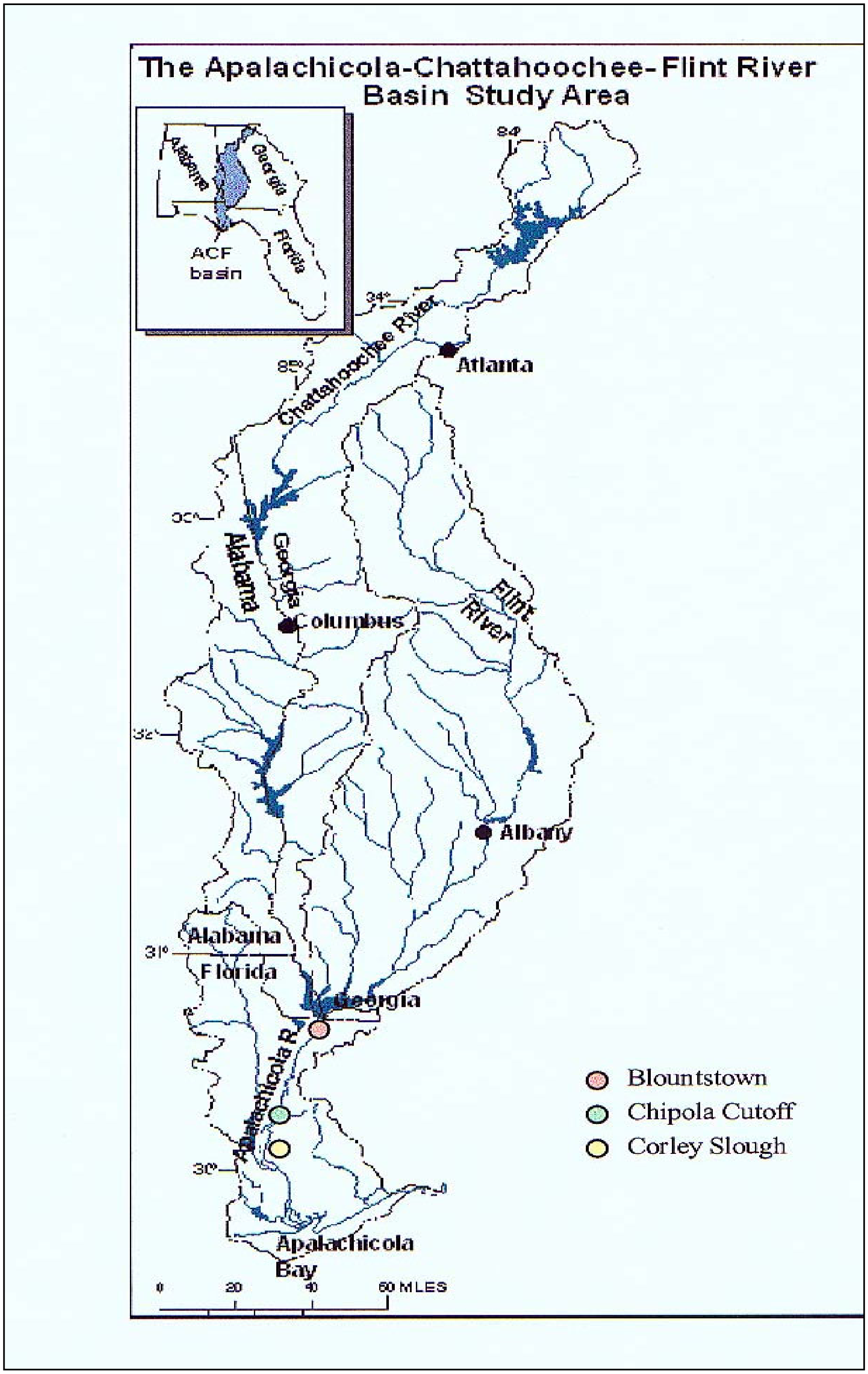

Figure 1. Apalachicola-Chattahoochee-Flint Waterway drainage basin

In 1987, mechanical redistribution was first used to manage the limited capacity of Disposal Site 43 (NM 37) (see Figure 2). Mechanical redistribution is accomplished by regrading the dredged material placed on the bank at Site 43. This practice may include reshaping the on-bank disposal site to prepare for mechanical redistribution by "mounding" the dredged material on the site adjacent to the river's edge. When river stages are forecast to rise for extended flow events, bulldozers push the material into the river. Mechanical redistribution normally occurs in the late fall and winter months prior to the onset of sustained high flows during the winter and spring. The sediment management goal of mechanical redistribution is to utilize the river's natural sediment transport capabilities to restore capacity to the on-bank disposal site prior to the next dredging season.

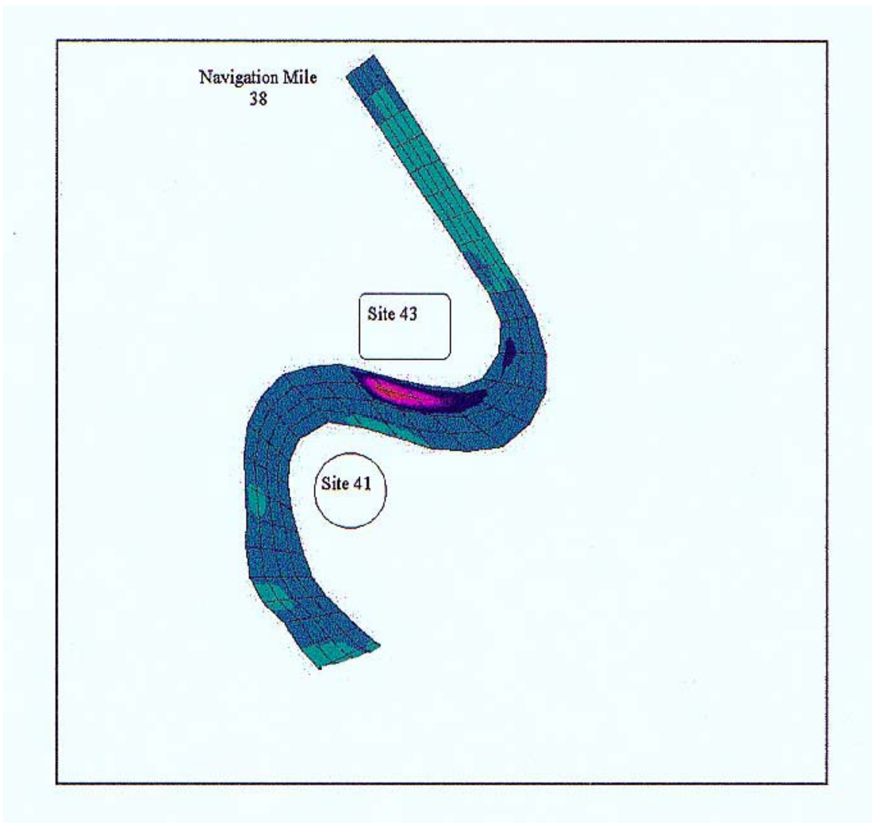

Figure 2. Site map of disposal areas 43 and 41

CH3D-SED Model: The CH3D-SED model makes computations on a curvilinear boundary-fitted planform grid. Physical processes that are modeled which impact circulation and vertical mixing in a wide range of water bodies include tides, wind density effects (salinity, temperature, and suspended sediments), freshwater inflows, turbulence, and the effect of the earth's rotation. The boundary-fitted coordinate feature of the model in the horizontal dimensions provides grid resolution enhancement necessary to adequately represent navigation channels and irregular shoreline configurations of the water body. The governing partial differential equations that are solved represent the conservation of momentum of the flow field, conservation of water volume, conservation of heat, conservation of salt, and conservation of suspended sediment, along with

an equation of state relating the water density to the salinity, temperature, and suspended sediment. Details concerning the model can be found in Johnson et al. (1991).

Sedimentation computations are based on a two-dimensional solution of the conservation of mass equation for the channel bed, i.e., the Exner equation, and the three-dimensional conservation equation for suspended sediment transport. The sediment bed is assumed to be composed of several layers including an active layer on the top (Figure 3).

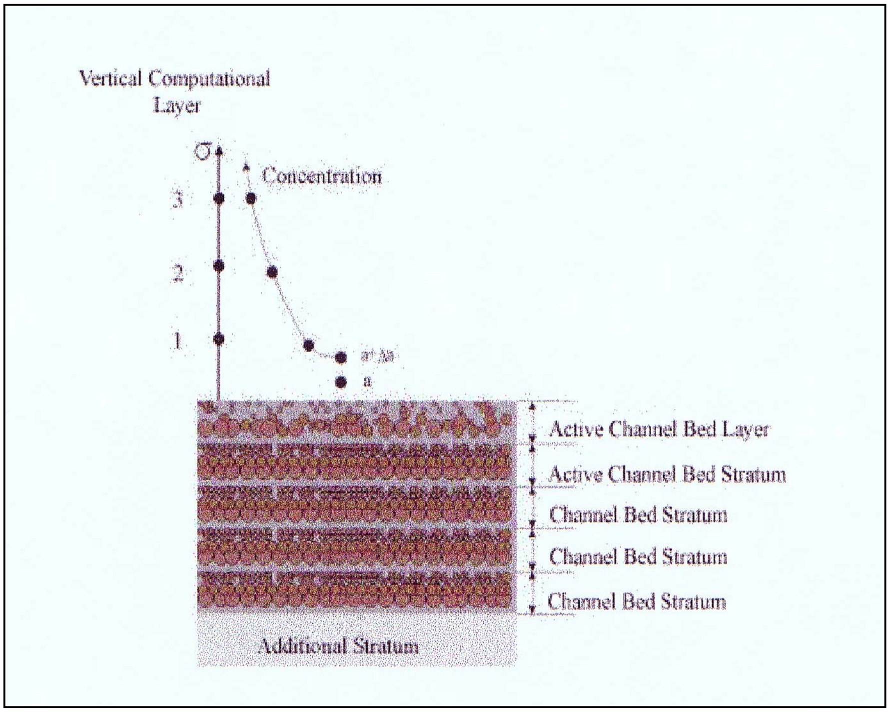

Figure 3. Bed sediment structure

The active layer description and hiding effects due to nonuniform bed material gradation, along with the manner in which sediment moves along the bed layers illustrated in Figure 3 are described in Spasojevic and Holly (1994). A unique feature of the mobile bed model, CH3D-SED, is the allocation of bed material transport as either bed load or suspended load. The sediment transport algorithms independently account for the movement of sediment as either bed load or suspended load, and also allow for the exchange of sediment between these two modes of transport. The bed-load flux predictor, as well as the relationship which relates the suspended load to the total load (bed load plus suspended load), was developed by Van Rijn (1984 a, b).

Model Data Requirements: Data requirements include water depths prescribed on the computational grid, initial conditions within the model domain, and upstream and downstream boundary conditions. The river geometry was obtained from the 1998 hydrographic survey performed by the U.S. Army Engineer District, Mobile. The alignment for the navigation channel was determined using the channel depths reported in the hydrographic survey and dredging records.

In addition to accurate geometric representation of the domain, appropriate hydraulic data and sediment concentrations must be prescribed at the inflow and outflow boundaries. At every location where water enters or exits the computational domain, either the stage or discharge must be specified along with the suspended sediment concentration of the inflowing water and the grain-size distribution for the material entering those cells. Model boundary conditions were based primarily on historical data collected on the river.

For this application, a discharge was specified at the upstream boundary, and a stage was specified at the downstream boundary. The downstream boundary stage was established using U.S. Geological Survey (USGS) gage records from October 1989 to September 1998. The upstream discharge was based upon a historical annual average hydrograph (Figure 4).

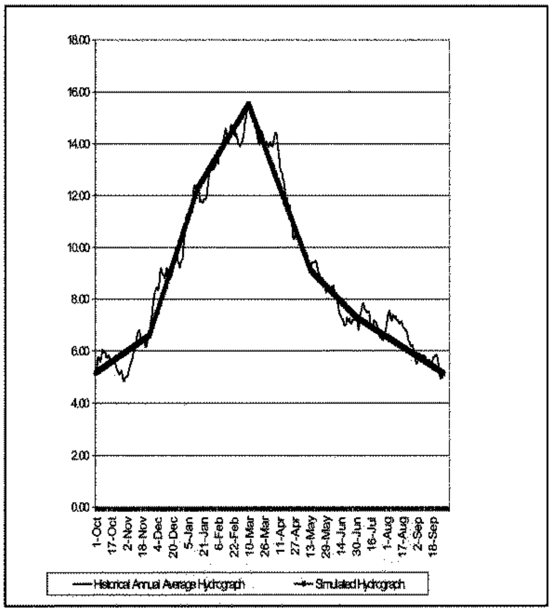

Figure 4. Historical annual average hydrograph
at Blountstown

As noted, the suspended sediment concentration must be specified at every location where water enters the computational domain. Sediment concentrations are specified for each size fraction for each cell in the water column at inflow locations, i.e., a vertical sediment concentration profile is described. The inflowing suspended sediment concentration and the grain-size distribution at the upstream boundary were based on data collected in May 1998 by the Mobile District. These data, collected from 2 May 1998 (the day before mechanical redistribution), through 5 May 1998, included discharge measurements, suspended sediment samples, and bed material samples. Analysis showed that the suspended samples consisted of 85 percent fine sand, 10 percent medium sand, and 5 percent silt and clay. Based on the data collected at NM 37.8, the model inflow concentration was set at 30 ppm for fine sand and 10 ppm for medium sand. The grain-size distribution for the riverbed material must also be specified in the model. Based on the data collected, the specified grain-size distribution was 35 percent coarse sand, 51 percent medium sand, and 14 percent fine sand. Finally, sediment entering the model

from sediment redistribution must also be described. Based on sediment data collected during 1999 from Site 43, the grain size of the sediment being mechanically redistributed was specified as 0.355 mm.

Numerical Representation of On-Bank Mechanical Redistribution: As previously stated, the dredged material is mounded at the disposal site near the river's edge. The mounded material is then pushed into the river using bulldozers when river stages are forecast to rise for extended periods. Depending on the amount of material, the entire operation can take on the order of days. To simulate this operation in the model, the appropriate mass of sediment, expressed as sediment concentration attached to a small lateral discharge, was introduced into cells adjacent to the bank disposal site over a specified period of time.

Because the ultimate fate of material disposed depends on the river's capacity to transport sediment, simulation of such an operation must also include the transport of sediment naturally occurring in the river. Thus, to be able to distinguish the disposed material from the naturally occurring material transported by the river, the disposed material is classified as a separate sediment class. Of course, in many cases the same sediment characteristics are prescribed for the disposed sediment as for the in-river sediment.

Numerical Grid: To develop an adequate computational model it is important to select an appropriate level of grid discretization. Adequate resolution should yield sufficiently accurate results while producing a model that minimizes computational requirements. Preliminary calculations were made to determine an adequate level of discretization for the Corley Slough model that resulted in computed results that compared well with observed data when reasonable values for model parameters were selected. A portion of the grid used is shown in Figure 5.

Model Validation: The only data available for validation of the computed hydrodynamics were water-surface elevations at the upstream end of the model. Recall that the water discharge is specified at the upstream end, with the water-surface elevation then computed from the conservation of volume equation. Good agreement (within 0.03048 m (0.1 ft)) was achieved between the model and observed stages. It is realized that the preceding result does not constitute a full hydraulic validation. However, the good agreement achieved in the sediment computations, shown in Figures 6 and 7, implies that the hydraulic performance is adequate. With the numerical model considered to be an adequate representation of the hydraulics and sediment transport in Corley Slough, it was then applied to predict the fate of dredged material disposed by mechanical redistribution.

Simulation of Mechanical Redistribution: A variety of mechanical redistribution scenarios were simulated in the original study, including the base condition with no mechanical redistribution. Only one scenario (scenario 2 in the original study) will be discussed here to illustrate the technique. Figure 8 shows the location of Corley Slough, key river miles, and the area of mechanical redistribution.

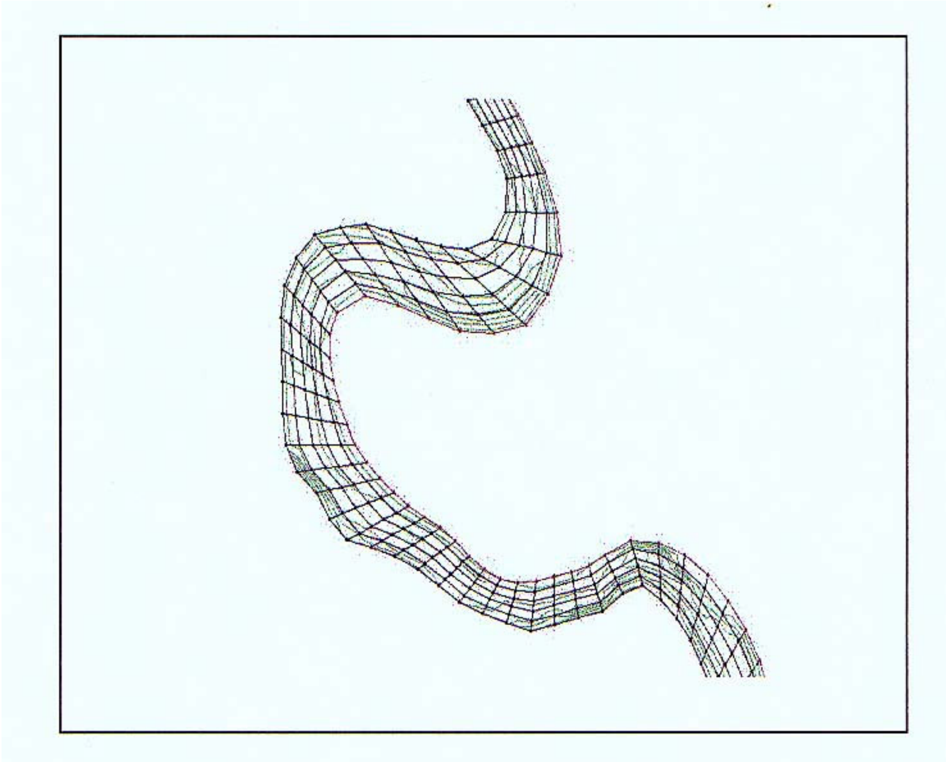

Figure 5. CH3D-SED grid (233 cells long by 5 cells wide by 3 cells deep) from NM 34 to NM 37

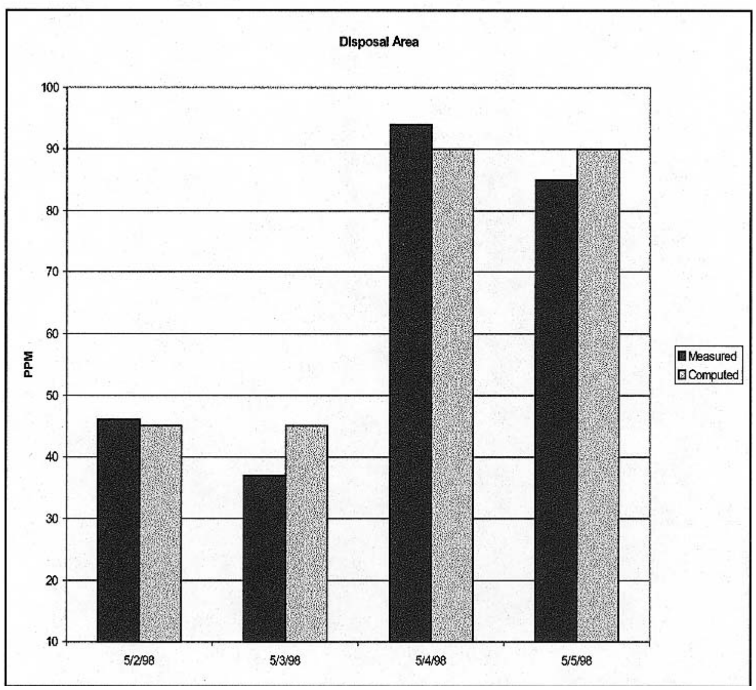

Figure 6. Comparisons of suspended sediment concentration at the disposal area

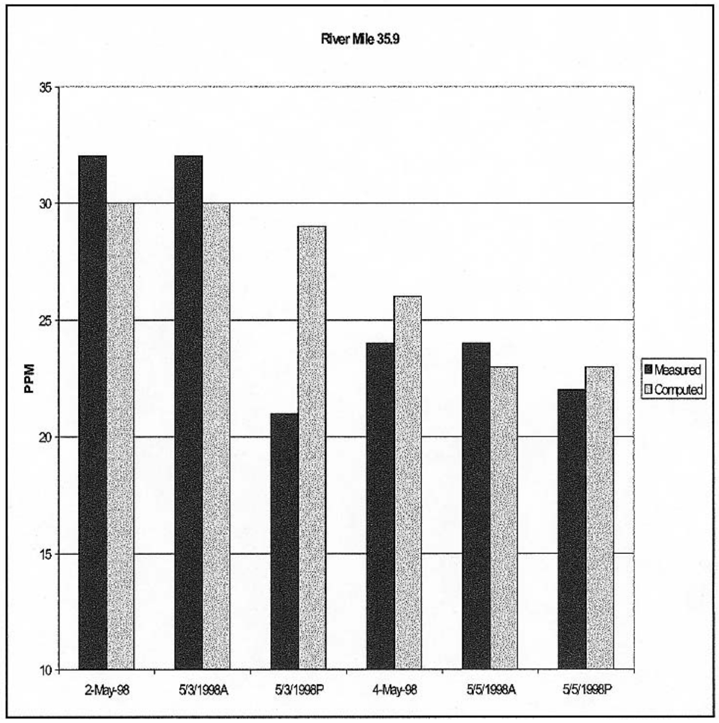

Figure 7. Comparisons of suspended sediment concentration at NM 35.9

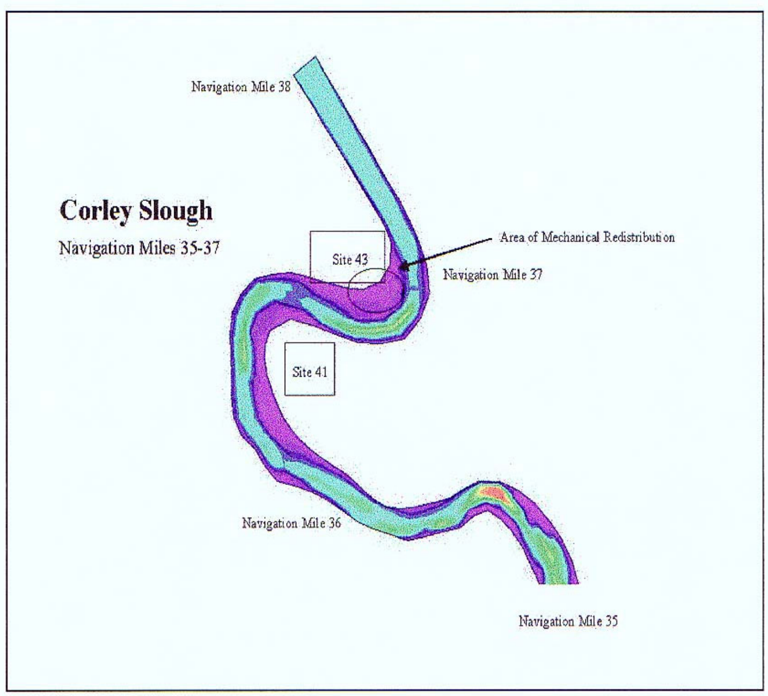

Figure 8. Site map of Corley Slough, including disposal areas 43 and 41

In scenario 2, disposal sites 41 and 43 received the estimated dredging quantities normally removed from the Corley Slough reach. Records from recent years show that approximately 38,227.74 cu m (50,000 cu yd) are normally placed on Site 41 and 76,455.49 cu m (100,000 cu yd) on Site 43. The 76,455.49 cu m (100,000 cu yd) of dredged material placed on Site 43 were mechanically redistributed, but no mechanical redistribution occurred at Site 41. Therefore, only natural erosion during high-water events occurred at Site 41.

To account for the material placed on Sites 41 and 43, the bottom elevation was increased at those areas in the computational grid. As previously mentioned, mechanical redistribution was accomplished by specifying a sediment boundary condition attached to a small inflow (about 4 percent of the river discharge during the mechanical redistribution period). Modeling also included the contribution of highly erosive banks in the reach. The contribution of sediment from these locations was accounted for by allowing the banks in these areas to erode.

Scenario 2 was run for 1 year, with mechanical redistribution initiated on day 88. Disposal of the bank material at Site 43 continued for 14 days. During mechanical redistribution at Site 43, the concentration of disposal material was 6,000 ppm. As the sand was injected into the model cells covering Site 43, some sand immediately settled and was redeposited at the site with the remainder transported downstream from the site. The bed-elevation change at day 96 is shown in Figure 9. Model results indicated that before the onset of mechanical redistribution, background concentrations of suspended sand were about 10 ppm, whereas, during redistribution, maximum concentrations of about 40-50 ppm were computed. By day 138, Figure 10 shows that, as the river discharge increased, sand on Site 43 began to erode, but material continued to be deposited in the adjacent channel. The channel deposition is likely due to sediment entering the upstream boundary as well as from eroded sand that redeposits there. At the end of the year-long simulation, a maximum of about 0.4572 m (1.5 ft) of sand was deposited at Site 43 (Figure 11).

Summary: Using a three-dimensional numerical sediment transport model, CH3D-SED, as the framework, a methodology for the simulation of the fate of dredged material placed on river banks and subsequently pushed back into the river before the onset of rising river stage, i.e., mechanical redistribution, has been applied to the Apalachicola River. This methodology involved the modification of CH3D-SED to handle mechanical redistribution of sediment, as well as analysis tools to aid in interpreting results. With this modeling tool, the ability of the U.S. Army Corps of Engineers to effectively manage sediment in rivers and streams is enhanced.

RED RIVER AT JHO LOCK AND DAM APPLICATION: Lock approach channels can have navigation problems caused by adverse currents in the vicinity of the approach channel. Navigation can be restricted by sediment deposition along the approach channel, causing shallow-water depths and requiring frequent maintenance dredging. Historically, both types of problems have occurred at the JHO Lock and Dam downstream approach channel. Multidimensional numerical hydrodynamic and sedimentation models can be used to address these types of issues.

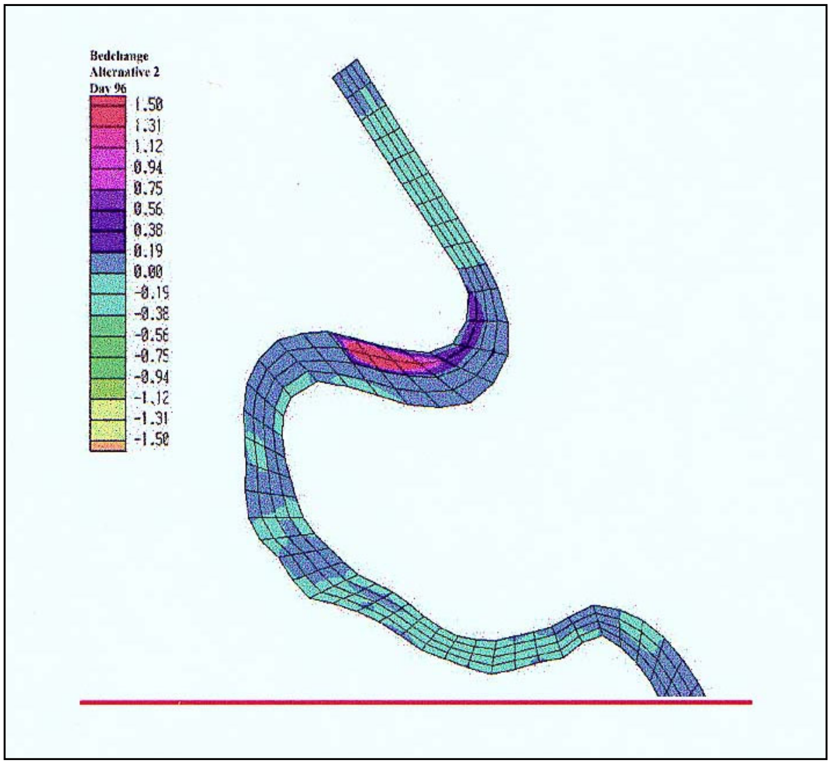

Figure 9. Scenario 2 bed elevation (ft) change on day 96
(To convert feet to meters, multiply by 0.3048)

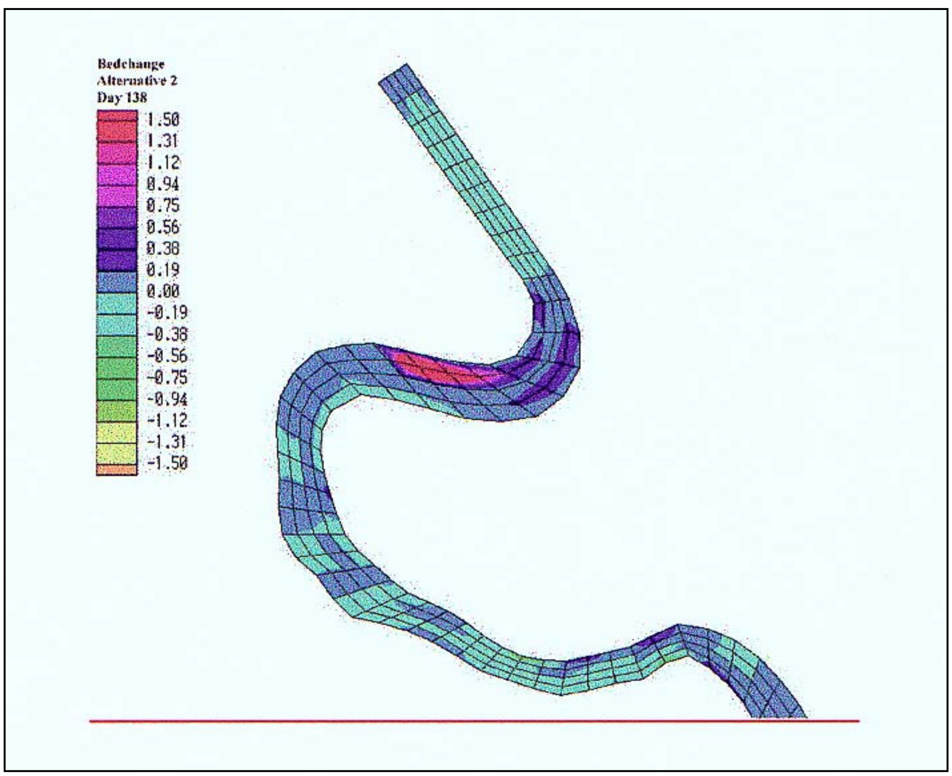

Figure 10. Scenario 2 bed elevation (ft) change on day 138

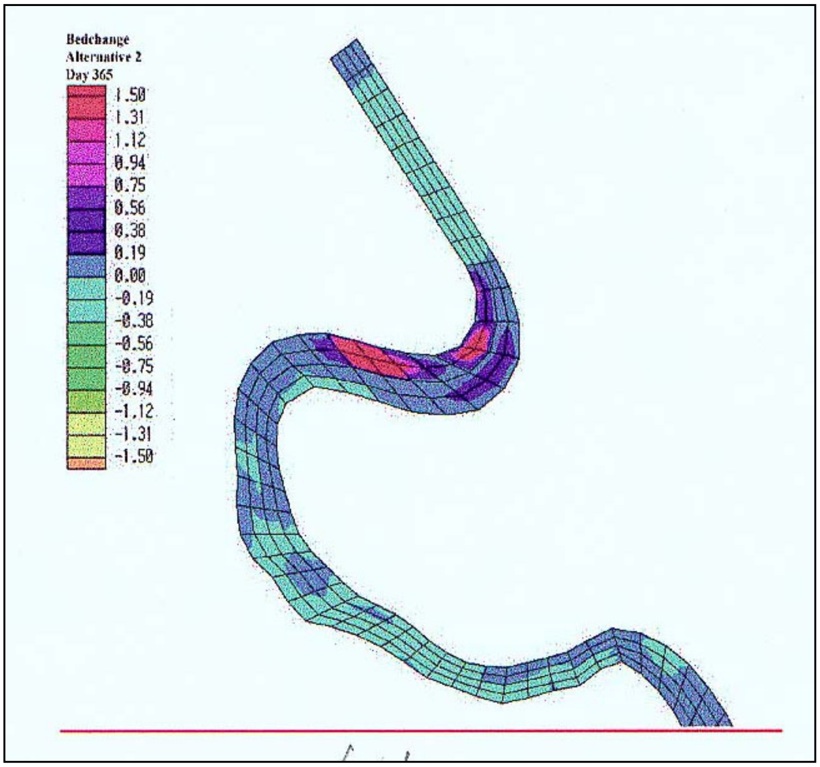

Figure 11. Scenario 2 bed elevation (ft) change on day 365

Background: The JHO Lock and Dam is located on the Red River, south of the Alexandria and Pineville, LA area (See Figure 12). The JHO structure is the second in a series of locks and dams on the J. Bennett Johnston Waterway, which provides a navigable route from the Mississippi River to Shreveport, LA. The JHO Lock and Dam was put into operation in November 1987, and mid to high river stages (15.25 m (50 ft) and above) resulted in navigation and shoaling problems compounded by the formation of eddies in the downstream approach channel.

Present measures to control the currents and sedimentation in the downstream approach channel include a large submerged dike of varying height to shield the approach channel (Figure 13). The dike has allowed waterway operation during higher flows than before, but vessel traffic encounters dangerous crosscurrents while approaching the lock guide wall. High approach channel shoaling rates are a serious maintenance problem.

RMA2-SED2D Model: The RMA2-SED2D model actually consists of two uncoupled models: RMA2 and SED2D. RMA2 is the hydrodynamic model and SED2D is the sediment transport model. The models are run sequentially, with output information from RMA2 being passed to SED2D as input information.

RMA2 is a two-dimensional depth-averaged (vertically homogeneous fluid) finite element hydrodynamic numerical model that computes water-surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields. RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are

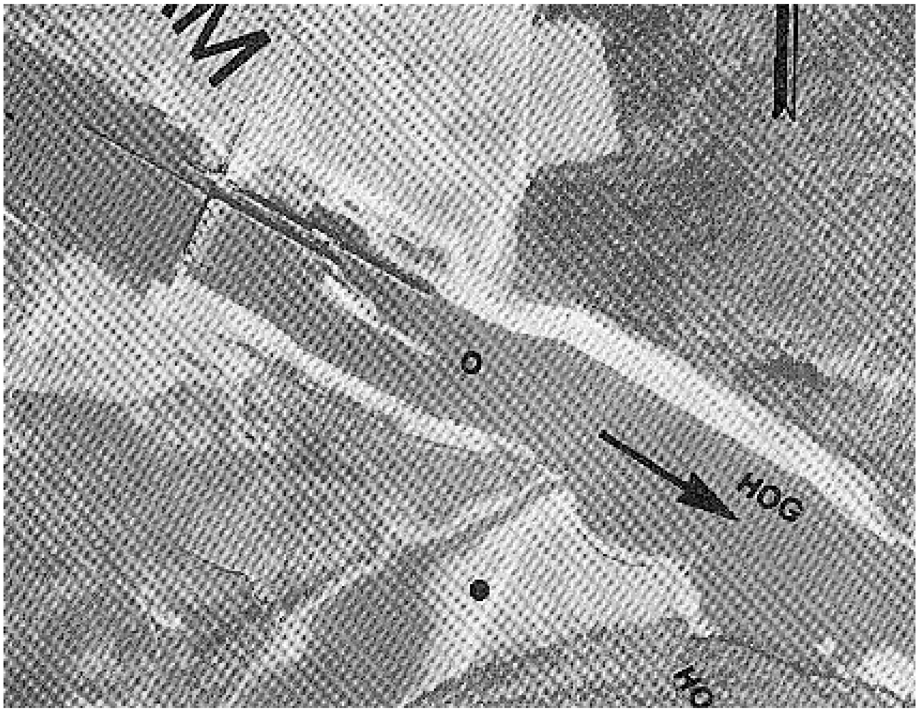

Figure 12. Aerial photo of John H. Overton Lock and Dam, Red River, LA

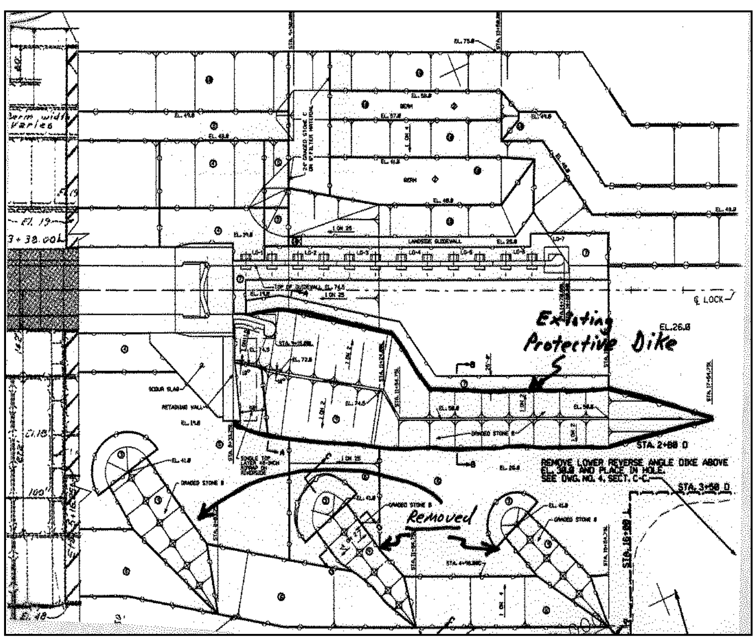

Figure 13. Existing protective dike adjacent to downstream lock approach

used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analyzed. RMA2 is a general purpose model designed for far field problems in which vertical accelerations are negligible (hydrostatic pressure), and velocity vectors generally point in the same direction over the entire depth of the water column at any instant in time. As such, it is

not intended to be used for near field problems where vortices, vibrations, or vertical accelerations are of primary interest. Vertically stratified flow effects are beyond RMA2 capabilities. RMA2 does have wetting and drying features and can simulate the impact of flow control structures such as weirs and culverts (U.S. Army Engineer Waterways Experiment Station 1995).

SED2D can be applied in areas where flow velocities can be considered two-dimensional in the horizontal plane (i.e., the speed and direction can be satisfactorily represented as a depth-averaged velocity). It is useful for both deposition and erosion studies and, to a limited extent, for stream width studies. The program treats two categories of sediment: (a) noncohesive, which is referred to as sand; and (b) cohesive, which is referred to as clay. Either steady-state or transient problems can be analyzed. The exchange of material with the bed can be calculated or suppressed. Default values can be used for many sediment characteristics or these values may be prescribed by input data. Either the smooth wall velocity profile or the Manning's equation may be used to calculate bed shear stress due to currents. Shear stresses for combined currents and wind waves may be calculated. Both clay and sand transport may be computed, but the model considers a single, effective grain size during each simulation. Therefore, a separate model run is required for each effective grain size. Fall velocity must be prescribed along with the water-surface elevation, x-velocity, y-velocity, diffusion coefficients, bed density, critical shear stresses for erosion, and erosion rate constants (ERDC 2000). The four major computations in the finite element formulation are:

a. Convection-diffusion governing equation

b. Bed shear stress calculation

c. Bed source/sink term

d. Bed strata discretization

Modeling Approach: Data requirements include river geometry to generate the computational grid, initial conditions within the computational domain, and upstream and downstream boundary conditions. The river geometry was obtained from hydrographic surveys and aerial photography. To better understand the eddy currents and shoaling patterns in the vicinity of the downstream approach channel to the lock, field observations were made and documented by U.S. Army Engineer District, Vicksburg, personnel. For this application, a discharge was specified at the upstream boundary, and a stage was specified at the downstream boundary. The upstream boundary was set at the tainter gates on the dam, and the downstream boundary condition was selected just over 1.6093 km (1 mile) downstream of the structure. Figure 14 shows the computational grid with inflow and tailwater specification locations. Model validation was based on its ability to simulate the observed currents within the study area, particularly the eddy circulation located in the vicinity of the lock approach channel.

Testing: Plans that involved dike additions and modifications and channel modifications were tested and analyzed. Both steady state and dynamic simulations were conducted.

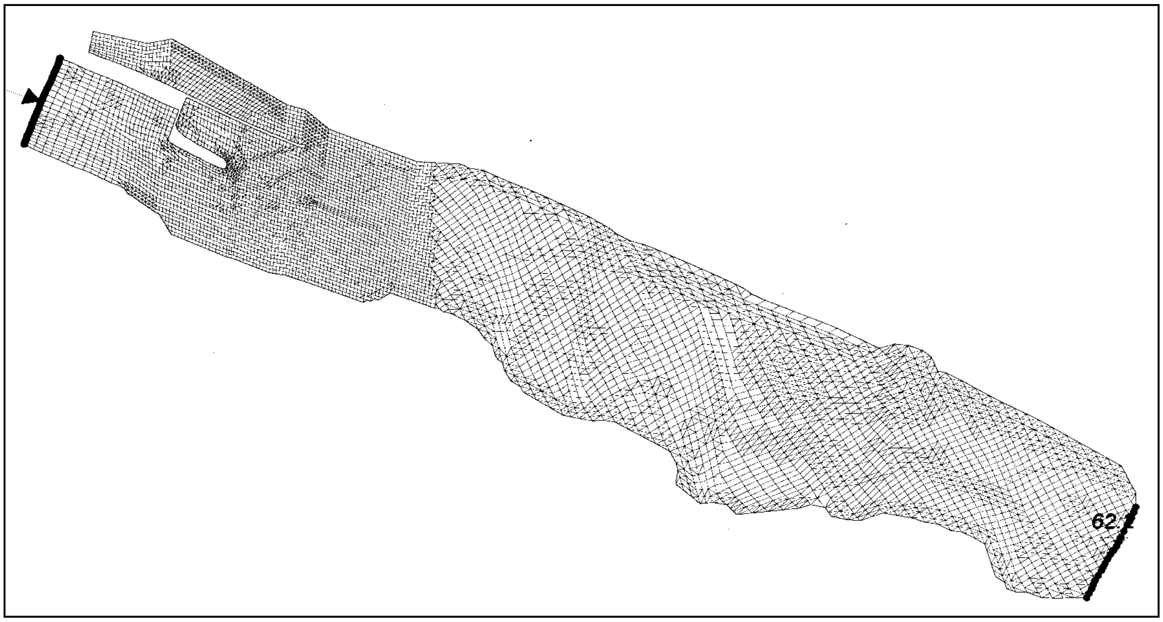

Figure 14. RMA2 high resolution grid – John H. Overton Lock and Dam

Results: To demonstrate RMA2 capability, current magnitude and direction results are presented for Plan B, which consists of channel widening (60.96-m (200-ft) increase) of the river channel adjacent to the lock chamber. These results are for a steady-state high event discharge of 3,511.28 cu m/s (124,000 cfs). Figure 15 shows the existing condition current pattern and Figure 16 shows the Plan B current pattern. As can be seen, the model shows a significant reduction in Plan B current magnitudes adjacent to the lock as well as a significant change in the circulation pattern downstream of the lock approach.

Once the RMA2 simulations are made, sedimentation simulations can be made using RMA2 velocities as input to SED2D. For demonstration purposes, a typical existing- condition sedimentation pattern, using a high-event hydrograph from RMA2, is shown in Figure 17.

SUMMARY: Two multidimensional model studies are presented that demonstrate available predictive capabilities using numerical models. These capabilities include not only hydraulics, but also sedimentation. These type models are applicable to both flood control and navigation studies in rivers and waterways.

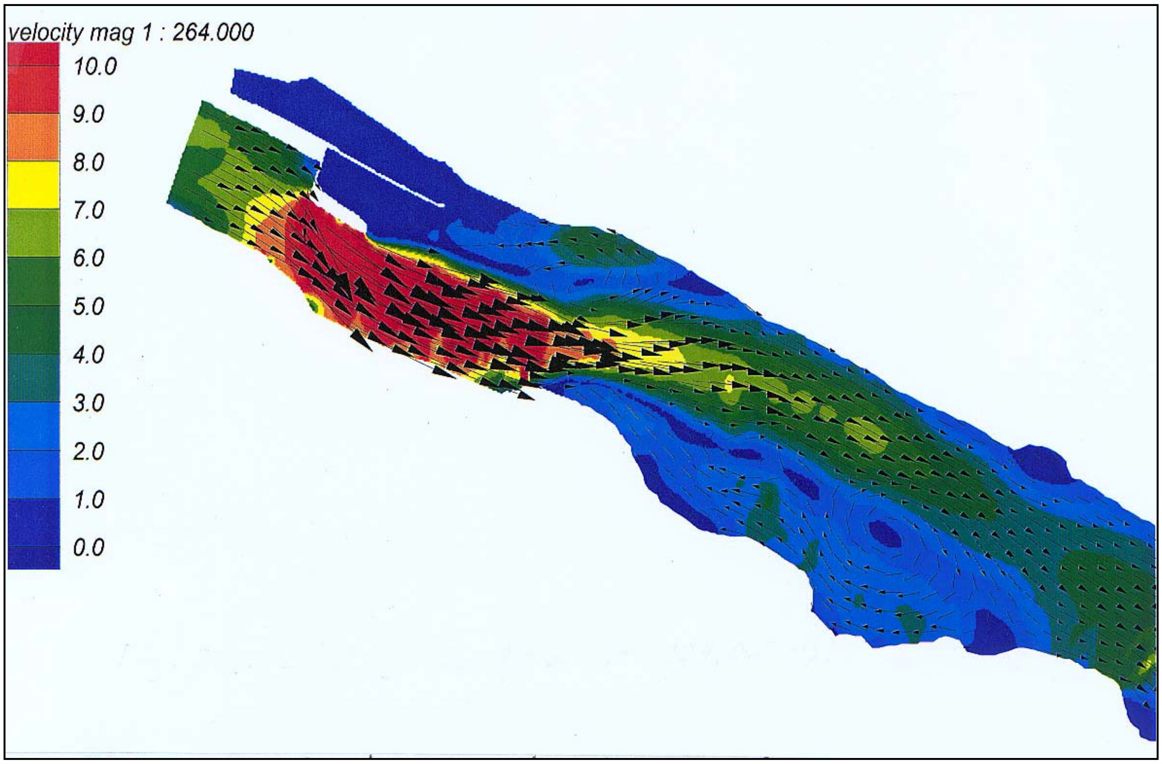

Figure 15. Velocity results from existing condition simulation at Q=124,000 cfs
(To convert to cubic meters per second, multiply by 0.02831685)

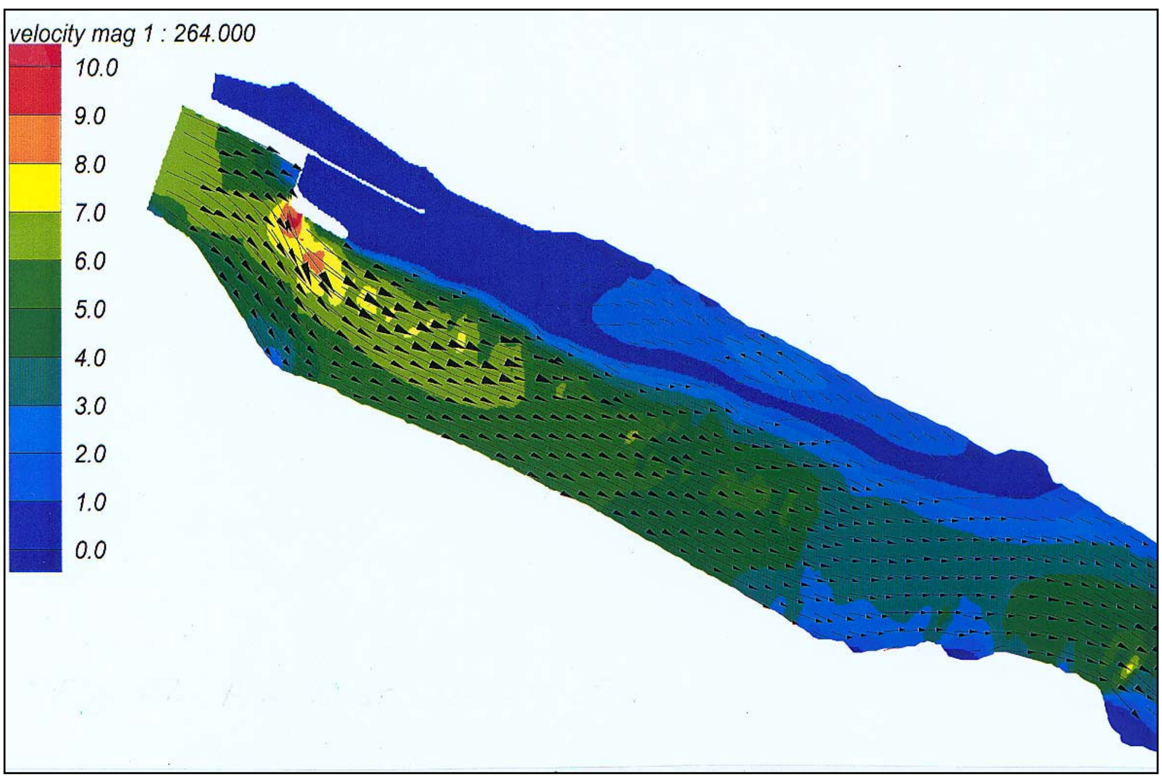

Figure 16. Velocity results from Plan 2 simulation at Q=124,000 cfs

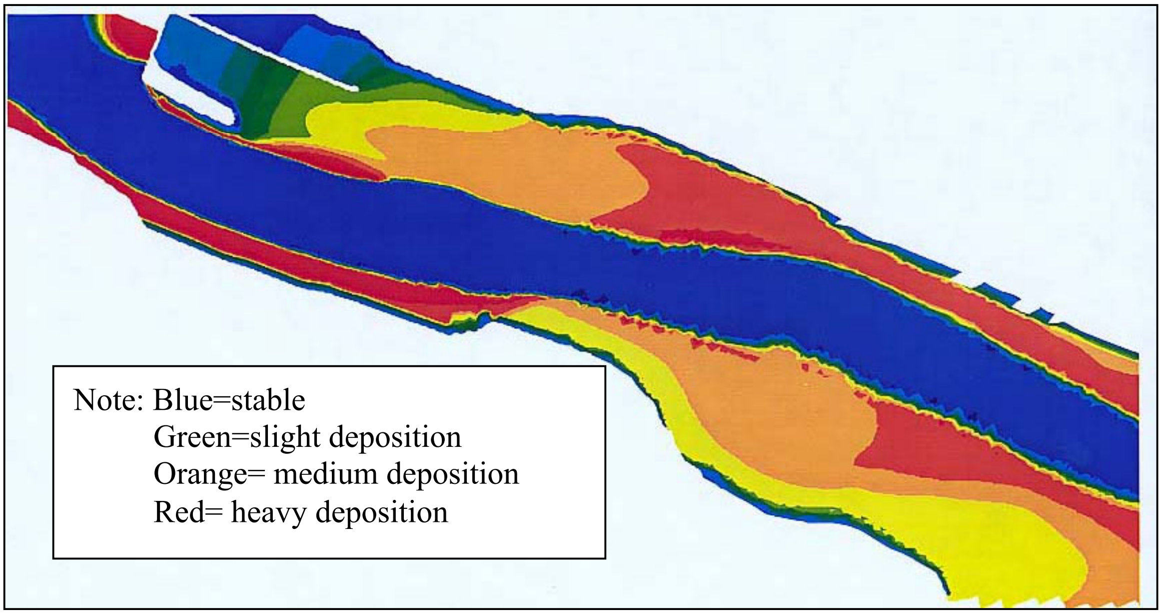

Figure 17. Typical existing condition sedimentation pattern

ADDITIONAL INFORMATION: Additional information may be obtained from Dr. Nolan K. Raphelt, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center (ERDC), 3909 Halls Ferry Road, Vicksburg, MS 39180, at 601-634-2634 or e-mail *Nolan.K.Raphelt@erdc.usace.army.mil;* or Mr. Michael P. Alexander, Hydraulics Branch, U.S. Army Engineer District, Vicksburg (CEMVK), 4155 Clay St., Vicksburg, MS 39183 or e-mail at *Michael.P.Alexander@mvk02.usace.army.mil*. This Technical Note should be referenced as follows:

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